Spectral Plane Method and Apparatus for Wavelength-Selective Optical Switching

FIELD OF THE INVENTION

[0001] This invention relates generally to the field of optical communications and in particular to a variable bandwidth tunable optical filtering device for selectively dropping or adding optical signal channels as a function of wavelength out of multi-channel optical signal transmitted through a multi-node optical communication network.

BACKGROUND OF THE INVENTION

[0002] In a Wavelength Division Multiplexed (WDM) optical communication network, a multiplexed optical signal at different wavelengths is transmitted between different network nodes of the network. Optical add/drop multiplexing (OADM) in a network allows connections to be made selectively between any two, but not necessarily restricted to two, different network nodes without disturbing the communication anywhere in the rest of the network.

[0003] In a simple OADM called a fixed OADM (FOADM), a fixed band-pass filter is used to selectively drop channels at a "drop" port or add optical signal channels at an "add" port (drop or add channels, respectively) at some pre-designated wavelength(s) at a network node. The remaining channels (express or through channels) are transmitted through an "express" (or through) port at the network node without any significant signal impairment. Wavelength selection at different network nodes is achieved by using different fixed band-

pass filters. Unfortunately however, this method offers limited flexibility in choice of wavelength(s) to be dropped or added and is not dynamically re-configurable.

[0004] For a more flexible and efficient network operation, dynamic and/or remote re-configurability of optical signal channels at any given network node is desirable. Re-configurable OADM (ROADM) dynamically and/or remotely selects wavelength signal channels to be dropped/added at different wavelengths. Advantageously, selection is done depending upon the network requirements and network dynamic conditions. .

[0005] In practice, all signal channels of a multiplexed optical signal are de-multiplexed at each network port to drop the desired optical signal channel(s) at that node or to add new optical signal channel(s). Typically, an ROADM comprises a de-multiplexer to separate the input wavelength signals into distinct paths; an array of 2-by-2 switches, one in each de-multiplexed path, to either pass or add and drop the signals at each of the wavelengths, and a multiplexer to combine the expresses and added channels and pass them to the designated output for further transmission. To effect this operation, a combination of wavelength de-multiplexing/multiplexing devices such as Arrayed Waveguide Grating (AWG) filters and switches at each network node are oftentimes employed.

[0006] Although such a device allows for any combination of channels to be added and dropped, it requires a large number of constituent parts and is therefore expensive. Moreover, the insertion loss and polarization-dependent loss of the system is typically high due to the large number of components that must be passed through from input to output.

[0007] Consequently, there exists a continuing need for improved apparatus and methods that provides for re-configurable optical add/drop multiplexing with reduced complexity and cost.

SUMMARY OF THE INVENTION

[0008] The present invention describes a novel multi-input/output variable bandwidth tunable optical filtering device and a method to operate the same as a ROADM in optical transport networks. In contrast with the prior art techniques, the single device offers remote and/or dynamically tunable ROADM operation with a high degree of flexibility.

[0009] The optical filtering device uses free-space diffractive wavelength demultiplexing and remultiplexing optics and an optical spectral plane filter with permanent physical patterns on a substrate.

[0010] The physical patterns on the spectral plane filter are designed to reflect, transmit or diffract the light either at the same angle, complementary angle, or some other angle depending on the lateral position of the incident light. Each different reflected/diffracted/transmitted angle corresponds to a different output port of the filtering device. Thus the spectral plane filter selectively directs different wavelength optical signal channels from one or more input ports to one or more output ports.

[0011] The spectral plane filter placed at the spectrally dispersed image plane of a multi-wavelength input optical signal selectively directs or switches one or more optical signal channels from a group of spectrally dispersed and spatially separated optical signal channels to different output ports. Using a single actuator with two degrees of freedom, both the center frequency of each filter in a predefined set of filter shapes and the filter selected can be changed.

Furthermore, certain types of filter switching operations may be performed without interrupting the optical signal channels that are not being switched.

[0012] For example, one may construct a multi-port ROADM filter that drops and/or adds a band of optical signal channels such that the center wavelength of the drop band can be changed without interrupting optical signal channels that remain in the express path (not dropped and/or added). The bandwidth of the filter may also be changed without interrupting add/drop and express channels that are not switched. The signals at different ports can then be processed locally or transmitted further as the requirement may be. By similar principles, signal(s) at different wavelength(s) from more than one input port can be combined into a common output port.

[0013] In operation, the multi-wavelength multiplexed input optical signal is first de-multiplexed by a dispersive element such as a diffraction grating. The portion of the multi-wavelength input optical signal that illuminates a physical pattern on the permanent spectral plane filter at the spectrally dispersed image plane is controlled by changing the relative position of the dispersed input spectrum and the spectral plane filter by laterally shifting the position of either the spectrum, the spectral plane filter, or some combination of the two.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] FIG. **1** is illustration of the principle of a variable bandwidth tunable optical filtering device for ROADM application in accordance with the invention;

[0015] FIG. **2** shows the effect of grating tilt on the spectrally dispersed image;

[0016] FIG. **3a** to **3d** shows different options for steering a spectrally dispersed beam;

[0017] FIG. **4** shows a schematic of a spectral plane filter to illustrate the principle of directing different wavelengths to drop and express output ports, respectively;

[0018] FIG **5a** to **5f** shows types of patterned permanent spectral plane structures;

[0019] FIG. **6** shows a specific example of static spectral plane with a triangular diffraction grating to illustrate the principle of signal drop operation;

[0020] FIG. **7** shows a schematic of a triangular grating to illustrate the principle tuning the center wavelength and/or bandwidth of optical drop channels;

[0021] FIG. **8** shows variable bandwidth ROADM drop spectrum;

[0022] FIG **9a** shows an example of a device having two inputs and two outputs according to the teachings of the present invention and FIG **9b** shows the inputs and corresponding outputs for the device depicted in **9a**;

[0023] FIG. **10** shows a double-pass configuration to implement ROADM function using a variable bandwidth tunable spectral filtering device device;

[0024] FIG. **11** shows configurations of guiding the optical output power to a fiber;

[0025] FIG. **12a** and **12b** show examples of angle/displacement conversion optics using a prism and gratings respectively, together with a spectral plane filter such that the output beams leave the spectral plane filter parallel;

[0026] FIG. **13** shows an example of a double-pass configuration to implement ROADM function using a variable bandwidth tunable spectral filtering device with a prism for angle/displacement conversion;

[0027] FIG. **14** shows an example of using ROADM in conjunction with a periodic AWG;

[0028] FIG. **15** shows a spectrum steering ROADM system using lateral actuation of the patterned spectral plane filter;

[0029] FIG. **16** shows a schematic arrangement to generate electrical feedback control signal for the tip/tilt grating stage for beam steering;

[0030] FIG.**17** shows the principle of feedback control using a combination of patterned spectral plane filter and a photo-detector; and

[0031] Fig.**18** shows an example of a MEMS tilt grating for beam steering application.

DETAILED DESCRIPTION OF THE INVENTION

[0032] Fig. **1** illustrates the basic concept of the optical filtering device of the present invention. Three optical fibers **101**, **113** and **114** connect to the optical system **100**, however, the configuration shown here can be scaled to larger number of input and/or output fibers. Any of the three fibers can be used as an input or an output port of the device. For illustrative purposes **101** is depicted as the sole input fiber.

[0033] With continued reference now to Fig.1, multi-wavelength optical input signal carried on optical fiber **101** exits the end facet and is collimated by a

micro-optic lens **102.** The collimated beam passes through a second micro-optic lens **103** slightly off-center from the optical axis so that the input signal is focused to a focal point **104** at an angle to the optical axis forming the source for the spectrally dispersive image system. The combination of the micro-lenses **102** and **103** may result in an anamorphic optical system producing either a symmetrical or asymmetrical beam with the ratio of the lengths of the major and minor axes of the elliptical beam cross section chosen to be some value between 1 to 10. The other micro-lenses **112** and **122** may be identical to **102** so that the same asymmetry is applied to any beam emitted from any of the fibers **101**, **113** or **114**.

[0034] The input light from the focal point **104** is collimated by a lens **105** and illuminates planar reflective diffraction grating **106** mounted on a tip/tilt stage **107** capable of controllably rotating the grating **106** about multiple axes as directed by electrical signals received via electrical connections **108**. Each component of the multi-wavelength input signal is diffracted at a distinct angle by the grating **106** corresponding to its wavelength. The spectrally dispersed diffracted signals are focused by a second pass through lens **105** and are imaged in a line on a permanent static optical spectral plane filter **109**.

[0035] For illustrative purposes the spectral plane filter **109** in this example is shown to have two distinct regions –a uniform reflective field region **110** normal to the optical axis and a flat wedge shaped reflective region **111**, at a different angle. However, any other combination of reflective physical features on the spectral plane filter may be present. Generally speaking, each physical feature on the spectral plane filter directs those wavelength signals impinging on it at a particular angle to one of the several output ports. Moreover, the same spectral plane feature may direct light from one input fiber to one output fiber and from another input fiber to a different output fiber.

[0036] For example, in this case, the input signal channels striking the flat region **110** of the spectral plane filter **109** are reflected at a complementary angle back through the system and pass through point **104.** They are collimated by lens **103** and focused into the output fiber **114** by a micro-lens **112**. The wavelength signals striking the angled facet **111** are reflected at a different angle parallel to the optical axis. They pass through the point **104** and are collimated by lens **103** and focused by lens **122** into output fiber **113**. When used as a tunable drop filter, outputs **114** and **113** could be the express and the drop ports, respectively.

[0037] The arrangement in Fig. 1 is shown for illustrative purposes. The lateral position of the input and output fibers, and their corresponding micro-collimating lenses could be changed or interchanged in two dimensions across a plane normal to the optical axis, so long as the angles of reflection from spectral plane filter **109** are changed correspondingly. The relationship between the lateral positions of two fibers relative to the optical axis, and the angle of reflection required at the spectrally dispersed image plane needed to direct light from one fiber to the other is readily deducible from the basic principles of 4f imaging.

[0038] As can be appreciated, the optical filtering device may be designed for any number of drop ports, each corresponding to a different faceted region or regions on the spectral plane filter with a particular angle of reflection. Advantageously, multiple discontinuous facets may be included on the same spectral plane filter.

[0039] Continuing our discussion of Fig.1, the multi-wavelength input optical signal is dispersed by grating **106** into a column of light spots on the spectral plane filter. The position of each spot is determined according to the wavelength of each component of the input signal. More specifically, the

permanent spectral plane filter **109** has no controls to change the effect it has upon the multi-wavelength input optical signal. In the device shown in Fig. **1**, the lateral position of the dispersed spectrum is controlled by tip/tilt stage **107** to rotate the grating **106** to the appropriate angle around its X-axis and Y-axis. Tilt of the collimated beam translates into lateral shift of the dispersed spectra on the spectral plane filter **109**. As can now be appreciated by those skilled in the art, instead of changing the position of the spectral plane filter, the lateral position of the entire dispersed spectrum is adjusted as a result of electrical signals received via electrical connections **108** so as to align the desired input signal channels with specific features of the permanent spectral plane filter to selectively direct those input channels to a specific output port.

[0040] The operation of laterally shifting the spectrum is understood with reference to Figs. **2a** – **2c**, which show the direct image of the face of input fiber **101** such that the central single mode optical fiber core **201** is visible. The dispersed spectral plane **109** is positioned below the input fiber **101** by appropriate initial alignment of the optical system. Three wavelength signals **202**, **203** and **204** (shown as **202a**, **203a**, and **204a**; **202b**, **203b**, and **204d**; and **202c**, **203c** and **204c** in Fig. **2A**, Fig. **2B** and Fig **2C**, respectively. For the purposes of illustration, **203(a-c)** are drawn corresponding to 1530 nm, 1540 nm, and 1550 nm wavelengths respectively. Additionally, while the dispersed spectral plane is shown positioned below the input/output fiber, it is not necessary that such positioning is required. More specifically, any relative orientation is contemplated and satisfactory for the purposes of the present invention.

[0041] With simultaneous reference now to Figs. **1** and **2(a-c)**, the three wavelength signals are all emitted from the single mode fiber core **201**, where they overlap. After making a first pass through the spectral de-multiplexing system **100** the three signals are imaged into a column of spots in the spectrally de-multiplexed plane **109**, where the vertical position of each spot is

approximately proportional to signal wavelength. In the initial alignment state of the system shown in Fig. **2a**, the column of spots **202a**, **203a** and **204a** is centered in the spectrally de-multiplexed plane **109**. Fig. **2b** shows the result when the reflective grating **106** is rotated about the X-axis. The spots have the same position relative to each other, but each spot is vertically shifted to new positions **202b**, **203b** and **204b**. Fig. **2c** shows the result when the reflective grating **106** is rotated about the Y-axis. The spots have the same position relative to each other, but each spot is laterally shifted to new positions **202c**, **203c** and **204c**. This type of actuation may be described as "spectrum steering", as the input spectrum is steered to the required position on the permanent spectral plane structure, as opposed to changing the spectral plane filter itself.

[0042] Fig. **3** shows several exemplary means for applying tilt to the reflected multi-wavelength signal. There exists a substantial body of engineering expertise in optical beam scanning systems, as described for example in the book "Optical Scanning", authored by Gerald Marshall, Ed., and published by Marcel Dekkar, Inc. in 1991. It is understood that one skilled in the art would be able to draw upon the prior art of such systems to construct related means for accomplishing substantially identical functions.

[0043] With continued reference to Fig.3 and in particular to Fig. **3a**, there is shown an illustrative single wavelength input beam **301** incident on reflective diffraction grating **106** which is mounted directly on 2-axis tip/tilt mount **107** used to control the direction of the diffracted output signal **302**.

[0044] In Fig. **3b** input beam **301** is reflected from a first-surface mirror **303** mounted on tip/tilt stage **107** and to illuminate reflective diffraction grating **106**, now stationary, such that the diffracted output signal **302** reflects again from mirror **303**. As in Fig **3a**, the tip/tilt stage controls the direction of the diffracted output, but in this configuration the output angle is approximately twice as

sensitive to tip/tilt stage angle as in Fig **3a**. In Fig. **3c**, the input signal **301** is diffracted from stationary reflective diffraction grating **106** and illuminates first surface mirror **303** mounted on tip/tilt stage **107**. Mirror **303** is oriented so that the reflected signal is incident on reflective diffraction grating **106** where it diffracts a second time. This configuration provides approximately twice the change in output angle as a function of input wavelength (spectral dispersion) as in configurations shown in Figs. **3a** and **3b**.

[0045] In Fig **3d**, input signal **301** is diffracted in passing through transmissive diffraction grating **304** then is incident upon first surface mirror **303** mounted on tip/tilt stage **107**. The reflected signal is diffracted again by a second pass through transmissive grating **304** to output **302**. In configurations **3c** and **3d**, where the scanned surface is the second reflective surface, rotation of the tip/tilt stage about the z axis controls lateral position of the imaged dispersed signals **202, 203** and **204** drawn in Fig. **2.**

[0046] In each of the systems shown in Figs. **3(a-c)**, the active moving element can be actuated by any of the means known in the art of optical scanning including, for examples, stepper motor driven screws, piezoelectric direct or screw drive actuators, torsional galvanometric actuators, thermal expansion actuation, and direct manual actuators. Other means known in the art for optical beam steering include micro-electro-mechanical systems (MEMS) actuators such as the devices used for constructing large port-count optical cross-connects. Such cross-connects typically involve two dimension arrays of dozens or hundreds of 2-axis gimbal-mounted beam steering mirrors, where electro-magnetic or electrostatic actuators control each mirror. In the current invention only a single, relatively large diameter, tilt-mirror is required but the same fabrication and drive techniques are applicable.

[0047] Principles of OADM application of the optical filtering device is described with reference to Fig. **4** showing a spectral plane filter **400** at the spectrally dispersed image plane. The multi-wavelength input signal is imaged as a column of light spots in the y-direction. The spectral plane filter may have different physical features that selectively reflect/diffract light at different angles. Each reflected/diffracted angle corresponds to a different output port. Variations in the physical features on the spectral plane filter along the y-direction result in different regions of the spectrum being reflected/diffracted at different angles. In general there may be multiple input fibers and signals from each input fiber will be incident on the spectral plane filter at different angles. For simplicity, one input fiber and one incident angle are assumed in the figure.

[0048] In this example shown in Fig. **4**, light spots from the dispersed image fall along a column in y-direction shown by line **401** on the spectral plane filter **400**. An input signal **403** at a given wavelength is reflected as **404** at an angle α, whereas another input signal **405** at a different wavelength is reflected as **406** at angle β. When the spectrum is translated in the x-direction to a new position shown by line **402**, angles of reflection may be changed to γ and δ, respectively. Although the incident angle of the input signals at these positions shown by **407** and **409** respectively does not change the signal is reflected along **408** and **410**, respectively. Thus, translating the spectrum in the x-direction switches input signals from one output to another on a wavelength-by wavelength basis.

[0049] Translating the spectrum in the y-direction changes the wavelength registration of the spectral plane filter. For example, if the spectrum is translated so that input signal **403** strikes the spectral plane filter at the same location previously hit by input signal **405**, it will be directed to the same output **406**, as input signal **405** originally was. Thus those skilled in the art can see that any wavelength can be directed to any of the output ports by translating the

dispersed input beam in x- or in y-direction without moving the spectral plane filter.

[0050] Many different types of optical filters can be used to achieve the said functionality in a spectral plane filter. For example, a permanent spectral plane filter can be constructed using a variety of techniques developed in prior art for constructing spatial optical filters on planar glass substrates or on curved or planar substrates made of metal, ceramic, plastic, semiconductor or crystal materials. In one example the spectral plane filter may comprise a hinged section of bulk or poly-silicon (mirror) that is lifted and held at an angle from the top surface of the substrate using any of a number of silicon micro-machining techniques. Both the tilted mirror and the non-tilted substrate surface are coated with a gold or other reflective coatings so that incident light is efficiently reflected.

[0051] As an example of a spectral plane filter, Fig. **5a** shows a reflection-based filter wherein the substrate **501** is patterned with a wedge shaped reflective feature **506**, made for example with a metal or dielectric multi-layer film. With simultaneous reference now to Fig **5a** and Fig. **4**, an optical beam **404** incident on the uncoated substrate will be transmitted through the substrate, while an adjacent optical beam **405** incident on the patterned feature will be reflected at a different angle.

[0052] Fig. **5b** shows a diffractive-based filter where a substrate **501** is patterned with a wedge-shaped region of reflective diffraction grating, such that an optical beam **504** which is incident on the uncoated substrate will be transmitted through the substrate, while an adjacent optical beam **505** incident on the reflective diffraction grating will be diffracted and reflected into one or more directions. In the example shown in Fig. **5b**, the incident signal **505** is split and diffracted into two output signals **508** and **509**. Such a diffraction grating may be made, for examples, with holographically recorded sinusoidal metal-coated

analog surface relief profile, or a lithographic digital computer-generated diffraction pattern. The same concept can also be implemented using a transmissive phase diffraction grating that would redirect the transmitted optical signals.

[0053] Fig. **5c** shows a reflection-based filter where a substrate **501** is fabricated with a surface relief profile then uniformly coated with a reflective layer such that an optical beam **504** which is incident on the flat portion of the substrate will be reflected into an output **510** symmetric about the surface normal, while an adjacent optical beam **505** incident on the patterned tilted feature **511** will be reflected into an output **512** propagating in an different direction determined by the surface normal of the tilted region.

[0054] Fig. **5d** shows a different reflection-based filter using a more complicated two-bounce concept where a substrate **501** is fabricated with a surface relief profile then uniformly coated with a reflective layer such that an optical beam **504** which is incident on the flat portion of the substrate will be reflected into an output **510** symmetric about the surface normal, while an adjacent optical beam **505** incident on the patterned tilted feature **513** will be reflected off the adjacent patterned surface feature **514** and then reflected into an output **515** propagating in an different direction determined by the orientations of the two surface features. In the example drawn in Fig. **5d**, the surfaces are oriented at 45° to the substrate normal such that the output signal **515** propagates backwards to the incident signal **505**.

[0055] Finally, Fig. **5e** shows a two-element filter composed of a roof prism **516** supported above a substrate **501** having a patterned reflector **517** such that an incident optical beam **518** will refract from a first facet of the roof prism and then be transmitted through the substrate, while an adjacent optical beam **519** will refract from a first facet of the roof prism then be reflected and

refracted from a second facet of the roof prism into output signal **520**. In the example drawn in Fig **5f**, the roof prism angles and separation from the substrate have been designed so that the output signal **520** is laterally shifted but substantially counter-propagating relative to the incident signal **519**.

[0056] The patterned features shown in Figs. **5(a-e)** can be created using known techniques in semiconductor device processing. For example, the filter of Fig. **5a** can be fabricated using, for example, evaporative deposition of metal followed by lithographic patterning and selective removal of a wedge-shaped region of metal to reveal the underlying substrate. It should be further understood that the wedge-shaped feature used in several of the examples of Figs. **5(a-e)** was chosen for illustration purposes only, and that the same concepts can be applied to implement arbitrary surface profiles, including both digital (binary) and analog (gray-scale) features. An example of gray-scale features would be a partially reflective coating (as in Fig. **5a**), or an angled reflective feature with continuously varying slope (in Fig. **5c**). It should also be understood that combinations of the concepts shown individually in Figs. **5(a-e)** are also possible.

[0057] With reference to Fig. **6,** a specific example of such a spectral plane filter **600** is described where the said filter has a specular region **601** surrounding a triangular diffraction grating **602**. The triangular diffraction grating **602** directs an input signal channel **608** to a drop port **609** whereas the specular surrounding field **601**, with no grating, directs an input signal channel **606** to an express port **607**. Of course, the grating could be written on the specular field region instead of on the triangle. Likewise both regions could consist of gratings of different period and/or orientation so as to direct incident light into different angles depending on which region is illuminated.

[0058] In one embodiment of the invention, the operation of such a filtering device for drop and express channels selection can be explained with

simultaneous reference to Fig. **1** and Fig. **6**. The multi-wavelength input signal striking the grating **106** is dispersed into a column of intensity spots in the dispersed spectral plane. By controlling the position of the tip/tilt stage **107** by electrical controls **108**, any portion of the dispersed spectrum can be imaged onto the triangular grating of the spectral plane filter shown in Fig. **6**. The light from optical signal channels imaged onto the grating of the spectral plane filter is reflected and directed to the drop port. The bandwidth of the light passed to the drop port can be varied by moving the dispersed spectrum in the x-direction, for example from position **603** to **604** along the base of the triangular grating. The center wavelength is tuned by moving the spectrum in the y-direction.

[0059] If the spectrum is imaged along a position **605**, then the center wavelength can be changed without changing the configuration of the spectral plane filter. That is, all the signals are continuously directed to a single output port. Similarly, it is also possible to direct any wavelength to the express port by simple translation operations. Those skilled in the art can see that with relatively simple translation operations a single spectral plane filter is continuously tunable in wavelength to drop any of the input signal channel(s) while directing the rest of the signal channels to other output ports. Since grating diffraction angle is wavelength dependent, it can lead to some wavelength dependent loss if uncompensated.

[0060] The operation of such a spectral plane filter to add a new wavelength channel(s) to one or a group of channels going to the drop port can be understood with reference to Fig. **7**. As has been explained earlier with reference to Fig. **6** that the signal bandwidth directed to the drop port is changed by simply translating the beam up or down along the base of the triangular grating on the spectral plane filter.

[0061] Turning our attention to Fig. **7**, it shows an example of an intensity profile of a dispersed multi-wavelength input signal striking the triangular grating **702** of the spectral plane filter **700**. Each intensity spot corresponds to a different wavelength component of the multi-wavelength input signal that will be directed to the drop port after reflection from the grating whereas the wavelengths falling outside this triangular grating region **701** are directed to the express port. By steering the beam from position **703** to position **704** on the grating an additional channel from the left of the spectral profile could be added to the drop port. Similarly by steering the beam from a position **704** to a position **705**, additional channels on the right could be added to the drop port. Those skilled in the art can see that moving the intensity profile on the triangular grating **702** along its sides will change the number of channels added to the drop port. The rest of the channels that fall outside the triangular grating will be directed to the express port

[0062] In telecommunication systems, it is important that the optical signal channels that are not being switched during a switching operation transmit uninterrupted. As can be appreciated, the example presented here satisfies that criterion.

[0063] In general, any signal channel that remains on a continuous homogeneous region (i.e. across which the angle of deflection as a function of input angle is constant) as the spectrum is translated laterally will not be interrupted during the switching or reconfiguration operation. Thus, the switching operation is said to be hitless for that optical signal channel. In this example, switching is hitless for all the optical signal channels that are directed to the express port initially and finally. Likewise, switching is hitless to the optical signal channels directed to the drop port initially and finally. Only those optical signal channels that are changed from the express port to the drop port or vice versa (i.e. switched are interrupted).

[0064] Fig. **8a** to **8c** shows graphs of the spectral response (the signal intensity as a function of signal wavelength) for tunable filtering device **100** during its operation. Fig. **8a** shows the spectral response in the initial alignment of the system. The graph shows a characteristic spectral peak **801** with a spectral bandwidth (labeled $\Delta\lambda_o$) and center wavelength (labeled λ_o) near the center of the spectral response curve. When diffraction grating **106** is rotated around its X-axis, the spectral response peak **802** shown in Fig. **8b** is shifted to a lower center wavelength λ_o', but the shape and spectral bandwidth λ_o is unchanged.

[0065] However, if instead of rotating the filter around its X-axis, the filter is rotated around its Y-axis the spectral response peak **803** shown in Fig. **8c** is unchanged in center wavelength λ_o and is instead changed in spectral bandwidth to a new value $\Delta\lambda_o$' determined by the width of the illuminated portion of the triangular grating.

[0066] One embodiment of the invention shown in Fig. **9a**, and with simultaneous reference now to Figs **9a** and **9a,** the device shown in **9a** utilizes a spectral plane filter **900** with a reflective facet **901** surrounded by a reflective field **902**. The facet is tilted with respect to the field at angle σ. The spectral plane filter **900** may be used in a reconfigurable optical add/drop switch that has two inputs and two outputs. Optical signals from one input, Input 1, are imaged onto the spectral plane filter at an angle α from the normal to the field. Optical signals from the other input, Input 2, are imaged onto the spectral plane filter at an angle β from the normal to the field. Wavelength signals reflected at angle $-\alpha$ are directed to Output 1' while those reflected at angle γ are directed to Output 2'. The angles are chosen such that $-\alpha = \sigma - \beta$ and $\gamma = \sigma - \alpha$. Thus, wavelength signals incident on the facet **901** at angle α are reflected at angle γ and directed to Output 2' while those incident on the field **902** at angle α are

reflected at angle $-\alpha$ and directed to Output 1'. Likewise, those wavelength signals incident on the facet **901** at angle β are reflected at angle $-\alpha$ and are directed to Output 1' while those that are incident on the field **902** at angle β are reflected at angle $-\beta$ and, in this example, are not directed to any output.

[0067] The spectrum is dispersed along the y-axis. The band of wavelengths that strikes the facet may be called the 'add/drop band'. With reference now to Fig **9a,** if we consider the express signal path to be from Input 1 to Output 1', then it is clear that those wavelength signals within the add/drop band are removed or dropped from the express path and directed to Output 2' while those outside the add/drop band continue on the express path. New signals within the add/drop band can be added to the express path at input2, from which they are reflected by the facet **901** to Output 1'.

[0068] The add/drop band can be tuned in wavelength by translating the imaged spectrum in the y-direction. By translating the spectrum in the x-direction, the add/drop switch may be turned off, so that the add/drop band disappears, or the bandwidth of the add/drop band may be tuned, if the facet has a triangular shape as shown in Fig. 6. Hitless reconfiguration is accomplished by first turning the switch off by moving all signals off the facet **901** along the x-axis, and then translating the spectrum in the y-direction. Finally the switch is turned on again at a new add/drop band with an x-translation.

[0069] In one embodiment of the invention shown in Fig.**10**, an add/drop system **1000** with double pass configuration is described. For simplicity of discussion the system **1000** is described with a single input port, a drop and an express port each.

[0070] With reference now to Fig.**10**, multiple- wavelength input signal enters the system via the input fiber port **1001** of a circulator **1002**. Input signal

is launched into the free space through the circulator port **1003** and is focused by a lens **1004** on the grating **1005** mounted on a tip/tilt stage **1006**. The stage can be controlled by electrical feedback signals through the electrical connectors **1007**. The dispersed input signal in the form of an array of intensity spots (Fig. 7) strikes the spectral plane filter **1010** after a second pass through the lens **1004**. The wavelengths that strike the region **1011** surrounding the aperture **1012** on the spectral plane filter are reflected back through the system and re-multiplexed by grating **1005**, and are imaged on to the fiber **1003** facet. The circulator separates this output signal and directs it to the express output port fiber **1014**.

[0071] Some portion of the spectrally dispersed input signal may pass through the aperture and some fraction of this light is collected by output fiber **1013**. If the drop fiber is multimode fiber and the aperture is smaller than the core diameter, the spectral shape of the drop band is determined by the width of the aperture along the y-direction. If the aperture is triangular in shape, then the drop bandwidth varies by translating the spectrum in the x-direction on the spectral plane filter **1010**. If the drop output fiber is a single mode fiber, then the drop band spectral shape is determined by the mode profile in the fiber (approximately Gaussian) in its central region and by aperture edges, in the wings of the band.

[0072] The device may perform hitless tuning by first translating the spectrum off the triangular aperture to a region where the entire signal is reflected and passed to the express output port **1014**. Then the spectrum can be translated in the y-direction without signal interruption. Finally, the spectrum is translated in the y-direction so that a new band is dropped. Depending upon the design of the spectral plane filter, e.g. a spectral plane filter with multiple different physical features, the application of a spectral plane filter can be extended to incorporate multiple drop output ports. Those skilled in the art can appreciate that multiple bands of variable bandwidth signals can be dropped by a single

spectral plane filter depending on the translation operations in x and/or y-directions. By extending the design of the system to incorporate multiple input ports (as shown in Fig. **9B**), wavelength “add” function is implemented for a completely reconfigurable ROADM to any optical network.

[0073] The drop output fiber **1013** may be a simple end-polished single mode fiber, as shown in Fig. **11a**. However, signals at the dispersed spectral plane with significant wavelength bandwidth cover an area which is large compared to the mode field diameter of single mode fiber, and so will not couple with uniform efficiency into a simple end-polished single mode fiber. Several possible configurations for optical coupling are shown in Figs. **11(a-c)**. Fig. **11a** shows a single wavelength signal **1101** incident on the central core **1102** of a single mode optical output fiber **1103**. Signals laterally misaligned substantially from the core by more than 10 microns will not couple into the output fiber.

[0074] Fig. **11b** shows a group of wavelength signals **1104** incident upon the multi-mode core **1105** of a multi-mode output fiber **1106**. Multimode optical fibers known in the art may have step index or graded index profiles, and can have core diameters that range from approximately 30 to 140 microns. In general, the larger the multi-mode fiber core, the broader the spectrum of signals that will couple directly into the multi-mode fiber.

[0075] However, modal dispersion in large core diameter multi-mode optical fibers restricts the distance that a high-speed data signal can be carried without impairment. Fig. **11c** shows a third alternative configuration where a group of wavelength signals **1107** is coupled by a condenser micro-lens **1108** to focus on the core **1109** of a single mode (or small core diameter multi-mode) output fiber **1110**. This configuration does not in general achieve perfect mode matching of any wavelength signal, and so cannot achieve loss less coupling. It

is possible however to adjust the lens focal length and position to achieve uniform excess insertion loss over a moderately broad acceptance spectrum.

[0076] The spectral plane filter described in Figs. **4, 6** and **9**, reflect the Incident input signal channels at different angles depending upon the physical features on the spectral plane filter. As a result, the output signal channels after reflection from the spectral plane filter go in different directions. Additional optical elements such as prisms, mirrors and chirped or non-chirped diffraction gratings can be used in conjunction with the spectral plane filter to redirect all the output signal channels parallel to the optical axis through the rest of the optical system.

[0077] As shown in Fig.**12a**, an additional angle/displacement converting optical element **1202a** is placed between the spectral plane filter **1201a** and the collimating lens such that all the output signal channels are made parallel with a fixed lateral separation after being deflected from the spectral plane filter. The angle/displacement conversion element **1202a** for example may be a prism. Alternatively, a prism may be replaced by a non-chirped or chirped grating structure as shown in Fig. **12b**.

[0078] With reference to Fig.**12b**, in this example the spectral plane filter and the angle/displacement optics have been combined into a single structure **1200b**. The reflective grating **1202b** at the dispersed image plane **1204b** on a glass substrate **1201b** forms the spectral plane filter whereas the transmission grating **1203b** on the opposite end forms the angle/displacement converting optics. An input signal channel **1205b** striking the grating **1202b** on the spectral plane filter returns to the same port as a drop signal **1206b** whereas another input signal channel **1207b** striking the spectral plane filter away from the grating **1202b** returns as an express channel **1208b**. The signal channels leaving the spectral plane filter become parallel. The gratings in this example can be

fabricated by lithographically defined etching of the substrate or by any other grating fabrication techniques.

[0079] Figure 13 illustrates how a prism may be used in the system to redirect the reflected beams to the appropriate output fibers. With reference to a single input system **1300** shown in Fig. **13**, a multiple-wavelength input optical signal is incident on an input fiber port **1301** of a circulator **1302**. The signal is launched into the free-space optics of the system through the fiber port **1303,** and is focused by the collimator lens **1304** on the dispersion grating **1305** mounted on a tip/tilt stage **1306**. The stage can be tilted around the x or the y-axis using a control signal transmitted through the electrical connectors **1307**.

[0080] The dispersed beam makes a second pass through the lens **1304** and is directed onto the spectral plane filter **1309** through a prism **1308** placed directly in the path of the dispersed spectrum. Optical signal channels incident on the angle reflector **1311** are reflected back along the incident path. The return beam from the spectral plane filter via the prism is directed to the drop port **1313** via the focusing lens **1304** and the circulator port **1303**. Optical signal channels incident on the flat field of the spectral plane filter are reflected at a complementary angle and pass back through the other half of the prism, resulting in the returning beam being displaced from the incident beam. The signal channels in this beam are re-multiplexed by the grating **1305** and passed onto the output port **1312**. In this application, prism **1308** may be replaced by a non-chirped or chirped grating structure as shown in Fig. **12b**.

[0081] Depending on the design of the physical features on the spectral plane filter, multiple numbers of output signals could be directed to different output fibers using a common optical arrangement. In the discussion here a single drop and express port each is shown for convenience. Tuning the center wavelength and the spectral shape of the signal going to the drop port is

controlled by the translation/rotation operations of grating **1305** via the tip/tilt stage **1306**. As can be appreciated, re-calibration of the feedback control is required. Thus those skilled in the art can appreciate that this device can be utilized in various different configurations to implement optical add/drop functionality in an optical network in a variety of ways.

[0082] Periodic Arrayed Wave Guide (PAWG) can be used to de-multiplex a band of wavelengths emitted from the drop port of the variable bandwidth tunable optical filtering device described herein. Unlike regular AWG device, PAWG is a passive colorless devices that can de-multiplex or multiplex any 8, 16, 40 or some other fixed number of contiguous wavelengths in a multi-wavelength optical signal. Any demultiplexers with this periodic property may be used, a PAWG is selected for illustration. A schematic of such an arrangement **1400** is shown in Fig. **14** where a variable bandwidth tunable OADM device **1401** as taught herein is used as a band-pass filter to separate any contiguous 8 or fewer channels from a multi-wavelength optical signal. In this implementation the variable bandwidth tunable filtering device **1401** separates a set of wavelengths at each node just like a fixed bandwidth band-pass filter. However, unlike a fixed band-pass filter, this device in this method has the flexibility of selecting any band of wavelengths out of all the input signal wavelengths without having to physically replace the filtering device.

[0083] Moreover, the OADM can be reconfigured to drop a different band of optical signal channels without interrupting the signal channels that are not reconfigured. The band of wavelengths so separated by the filtering device **1401** is further de-multiplexed by the PAWG **1402** for processing individual signal channels as required. The same combination of identical components **1401** and **1402** can be used at each network with the filtering devices at different nodes being tuned to different sets of wavelengths at the respective nodes in accordance with the network design rules. Since the tunable filtering device is not specific for a given channel spacing, this combination allows seamless

upgrade of channel spacing with the limitation on channel spacing imposed by the choice of PWAG and not by the variable bandwidth tunable filtering device. Therefore those skilled in the art can appreciate the versatility and potential of this filtering device and the method of OADM implementation in reducing the network complexity and cost.

[0084] All of the systems described so far use angular tilt of the collimated signal beams to introduce a lateral shift at the spectrally dispersed image plane. The same concepts for optical filtering using a permanent spectral plane filter can be also implemented using a physical translation of either the input fiber or the permanent spectral plane filter. A variety of physical translation actuators can be used to control lateral position, including for example threaded screws driven by stepper motors, by direct current motors, by piezo-electric actuators, or driven manually.

[0085] By way of an example, and with reference now to Fig. **15**, there is shown an optical filtering device that is functionally similar to the optical filtering device **1000**. An input signal carried on fiber **1501** is collimated by a micro-lens **1502** followed by a second micro-lens **1503** that focuses the input beam to spot **1504** at an angle to the optical axis in the lens. Lens **1505** re-collimates the beam and illuminates reflective diffraction grating **1506** that is now fixed in position. Each component of the input signal is diffracted at an angle corresponding to its wavelength, is focused by a second pass through lens **1505,** and is imaged as a column of spots onto a permanent spectral plane filter **1507.** The spectral plane filter in this case may be a triangular grating **1509** in a specular background **1508** as described in Fig. **6**, or other type of filter described in Fig. **5** that reflects a selected portion of the signal back through the optical system, into either of the output fiber ports **1514** or **1515** through the lenses **1513** or **1522**.

[0086] In this arrangement instead of using a tip/tilt stage for position control, the spectral plane filter **1507** is mounted on two-axis translation stage **1508** so that its lateral position can be directly controlled by horizontal (X-axis) and vertical (Y-axis) actuators **1511** and **1512**, respectively. In Fig. **15**, the two lateral position actuators are for example manual screws. Actuator **1511** then controls the center wavelength of the transmitted signal, and actuator **1512** controls the wavelength bandwidth of the transmitted signal. Equivalent lateral-shifting embodiments can be constructed for each of the systems described herein.

[0087] Closed loop control of the angular position of tip/tilt mount e.g. **107** in system **100** (Fig. 1) based on feedback from some measurement of position can enable greater accuracy and stability. Closed loop control can be based on an external measurement of the optical signal coupled into the output fiber as, for example, an optical spectrum analyzer elsewhere in the fiber optic communications system. It is preferable, however, to provide an internal measurement of the signal position.

[0088] A system **1600** with such a closed loop feedback position control is shown in Fig. **16**. Although functionally similar to the filtering device **1500** described earlier, this system includes a means for optically monitoring the position of the dispersed spectrum at the spectral plane filter. With simultaneous reference now to Fig.**16**, input signal at the fiber port **1601** passes through an optical circulator **1602** to the input port **1603** of the filtering device. Unlike in system **1500**, the dispersion grating **1608** is mounted on a tip/tilt stage **1609** with feedback control provided through the electrical connector **1610**.

[0089] The spectral plane filter **1613** in this case includes a number of elements. The first element is a reflective region **1615** that reflects light back through the system to output port **1620** through lens **1618**. The reflective field

1614 reflects light back into the circulator port **1603.** The circulator directs this return signal to drop output port **1619**. The reflective field contains a spatial filter **1616**, an array of transparent or semi-transparent slits that allow light to pass through the spectral plane filter to a large aperture optical detector **1617** positioned behind spatial filter **1616** such that any light that is transmitted through spatial filter **1616** is detected. The combination of spatial filter **1616** and detector **1617** registers an electrical signal in response to the spatial position of optical signals and so is useable for feedback control of tip/tilt stage **1609** or to detect changes in the center wavelengths of one or more of the optical signals passing through the optical filtering device.

[0090] The use of patterned apertures for feedback control is understood with simultaneous reference to Fig. **16** and Fig. **17**, which shows a closer view of the combination of the patterned spectral plane structure **1613**, patterned aperture **1616** and detector **1617** from optical filtering device **1600** of Fig. **16.** Referring to Fig. **17** now, a column of input signals **1701** corresponding to 6 wavelengths on the transmission grid (for example at 100 GHz pitch) illuminate a transparent substrate **1702** coated with a reflective layer except where patterned with sets of apertures **1703** and **1704**, and reflective regions **1705** and **1706** that reflect light at a different angle than the reflective field.

[0091] In general, multi-wavelength telecommunications systems use signal wavelengths that lie on the telecommunications standard ITU grid, which specifies allowed center wavelengths on a 50 GHz (0.4 nm) pitch. In specific applications, the signal wavelength may be known to lie on a restricted subset of these wavelengths, as for example in a C-band system with 40 signals at a 100 GHz pitch. Each wavelength signal can be expected to lie slightly above or below the target value, but the average of multiple signals is relatively accurate indication of the average signal wavelength. In any case, the relative position of any single wavelength signal is important in determining (and maintaining)

optimum performance of the multi-wavelength transmission system. Therefore a prior knowledge about the signals entering optical filtering device **1600** can be used to measure the wavelength of each single wavelength signal relative to the median position of the signals entering filtering device **1600.**

[0092] The column of intensity spots **1701** from the dispersed multi-wavelength input optical signal entering the filtering device are spectrally dispersed onto the aperture array **1703**. The lateral separation of the apertures is chosen to match the signal wavelength pitch such that the signal registered upon the detector **1617** (Fig. **16**) is a minimum for discrete alignments of tip/tilt stage **1609** (Fig. **16**) for which the actual wavelengths of the WDM channels present align, on average, with locations in the filter spectral response corresponding to the design wavelengths. In effect, the detector registers the convolution of the signal wavelengths with a comb filter designating the design values. Once the signals are roughly aligned, the analog electrical output signal from detector carried on electrical connections **1708** can then be used for accurate position feedback

[0093] Shown in Fig. **17**, are patterned mirrors **1705** and **1706** to reflect the signal of interest **1709** into the optical outputs. In this example the signal falling on detector **1707** is maximized when one of the wavelength channels **1701** is centered on the reflective surface **1706**. With appropriate design of the aperture pattern, a variety of position feedback systems can be implemented to accommodate specific filter functions and system environments.

[0094] Although all of the system embodiments described so far use reflective optical system geometries based on the reflective beam steering configurations shown in Figs. **4(a-d)**, it is also possible to construct an optically equivalent system using a transmissive beam steering means. Such means can include, for example, use of rotating prism pairs (e.g., William L. Wolfe,

Introduction to Infrared System Design, SPIE PRESS Volume TT24, Chapter 12), liquid crystal beam deflectors (e.g., R. McRuer et al, "Ferroelectric liquid-crystal digital scanner", Opt Lett. 15, pp. 1415-1417, 1990; see also US Patent 4,964,701) and electro-optic beam deflectors (e.g., J. Thomas and Y. Fainman, “Optimal cascade operation of optical phased-array beam deflectors,” Applied Optics, Vol. 37(26), pp. 6196-212, 1998).

[0095] In systems that use a second pass of the optics to recollect the filtered multi-wavelength signals into a single mode output fiber (e.g., Fig. **1**, **100**; Fig. **10**, **1000**; Fig. **13**, **1300**; and Fig. **16**, **1600**,) the ideal position of both the tilting mechanism and the diffraction grating is in the back focal plane of the large collimation lens (Fig. **1**, **105)**. This provides telecentric imaging, and optical coupling efficiency of the recollected signals into the single mode output fiber. This can be achieved using a bulk reflective grating directly mounted on a macroscopic optomechanical tip/tilt stage **107**, as drawn in Figs. **1.** It can also be achieved in a more cost-effective way by combining the reflective grating with a micromechanical tip/tilt device. Single-tuning axis micromechanical angle-tuned diffraction gratings suitable for laser tuning have been demonstrated in prior art, e.g. M. H. Kiang, et al, "Surface-Micromachined Diffraction Gratings for Scanning Spectroscopic Applications," Proc. Int. Conf. Solid-State Sensors and Actuators, Chicago, IL, June 1997.

[0096] Finally, a two-axis angle-tuned diffraction grating suitable for spectrum steering is shown in Fig. **18**. For ease of discussion a front and a side view is shown in Fig. 18a and Fig. 18b, respectively. With reference now to Fig. **18**, a planar silicon upper substrate is micromachined into a planar diffraction grating **1801** connected by two torsion bars to an inner gimbal ring **1802**, which is in turn connected by two torsion bars to an outer gimbal ring **1803**. The upper substrate is supported with an air gap above a lower substrate **1804** (Fig. **18b**) and is patterned with electrodes **1805** (Fig. **18b**) capable of creating an

electrostatic attractive force on a portion of the movable grating such that the angular position of the grating can be controlled by applying a combination of voltages to the control electrodes. Such a device can be fabricated using, for example, a silicon-on-insulator bulk silicon MEMS fabrication process where the diffraction grating is formed using binary or analog surface profile etching of a upper silicon layer, silicon oxide as a dielectric stand-off layer, and wafer bonding to join the top layers to a lower substrate which is patterned with the drive electrodes. Silicon is transparent to the telecommunications wavelength region, so it is possible to pattern the diffraction grating surface relief on either the top or bottom of the upper silicon layer, provided a reflective coating (typically one or more thin layers of metal) is applied to the grating surface relief pattern.

[0097] Functionally identical angle-tunable diffraction gratings can be constructed by fabricating a diffraction grating on any micromechanical structures developed to position a two-axis tilt mirror, including surface micromachining with electrostatic plate actuators, bulk micromachining with comb drive actuators. The grating would ideally be fabricated as a surface relief profile etched into the top planar structure. It is also possible to emboss a grating on the surface of an otherwise planar structure, as for example using a thin layer of epoxy which is shaped by physical contact with a master grating structure (a technique used in the art of replicating fixed surface relief diffraction gratings), or using a thin layer of optical sensitive material, such as photopolymer, and optically recording a holographic grating structure (a technique used in the creating of fixed holographic gratings).

[0098] Various additional modifications of this invention will occur to those skilled in the art. Accordingly, all deviations from the specific teachings of this specification that basically rely upon the principles and their equivalents through which the art has been advanced are properly considered within the scope of the invention as described and claimed.